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STATE-OF-THE-ART REPORT

on

SOLID-STATE, SELF-LUBRICATING MATERIALS FOR POSSIBLE USE IN PRECISION SLIP RINGS

to

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, ALABAMA

October 31, 1968

by

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INTRODUCTION

The development of miniature slip-ring assemblies for space applications has identified a need for improved electrical contact materials and lubrication systems to ensure the required reliability. To meet this need, a research program was undertaken by Battelle's Columbus Laboratories in April, 1968, on behalf of the NASA-George C. Marshall Space Flight Center under Contract No. NAS 8-21323. This state-of-the-art report on the applicability of solid-lubrication techniques to electrical contacts is one contribution to this program. The objective of this effort was to attempt to identify any solid-lubricant material systems that show sufficient promise for NASA's particular need to justify subsequent experimental evaluation.

The electrical requirements imposed on miniature slip-ring assemblies for the ST-124M guidance platform dictate the use of contact materials that are not susceptible to formation of insulating surface films. Since gold most nearly fulfills the requirements for low-energy contacts, it has been used for the slip-ring surface and is the major constituent in the brush rider. However, testing of the first generation of slip rings showed that even gold is susceptible to troublesome "friction-polymer" formation when operating for extended periods in the ST-124M Platform environment that contains organic vapors. The organic materials in the assembly that gave off deleterious organic vapors were identified under NASA Contract No. NAS 8-11403. Particular material substitutions and changes in assembly processing can probably reduce the harmful effects of the offending species to a tolerable level. Thus, the formation of insulating friction polymer on the contact surfaces can be placed under reasonable control. However, under "clean" experimental conditions, whereby friction-polymer formation is greatly reduced, high electrical noise still remains as a result of seizure and the resulting severe galling of the contacts. Where friction polymer is continuously produced, lubrication is sufficient to prevent galling. The need for reliable lubrication of the contacts which will minimize both galling and friction-polymer formation is therefore clearly identified.

Although the chemical inertness of gold precludes the classical boundary lubrication mechanisms that are effective with less-noble metals, numerous studies on fluid lubrication of gold have revealed that liquid lubricants do exist that are capable of adequately lubricating sliding gold contacts (at least over some range of sliding speed and contact temperature), provided gross quantities of lubricant are present. If the quantity of lubricant at the sliding interface is limited, adhesive wear and associated high electrical noise occur.* Effective lubrication by a liquid, therefore, requires the

* Of course, electrical noise can be high with a flooded contact if hydrodynamic effects occur. Such effects occur when the contact sliding speed and lubricant viscosity are of such magnitude that the contact lift is near the value of the contact load.

maintenance of gross quantities of lubricant at the contact interface, which suggests the need for replenishment of lubricant depleted by surface creep. Unfortunately, miniature slip rings for satellite applications inherently do not lend themselves to simple techniques for replenishment of liquid lubricants. Requirements of long shelf life, extended ground testing, and encapsulation make difficult standard techniques of lubricant replenishment – e.g., wicks, reservoirs, supply systems, or reapplication by disassembly. Therefore, a need exists for effective and reliable self-lubricating materials and lubrication techniques to ensure trouble-free operation of miniature slip-ring assemblies.

When the total problems of friction polymer, galling, and maintenance of liquid-lubricant films are considered, solid-film lubrication or solid-state self-lubricating materials appear as the desirable substitutes. Long life, low electrical resistance, low noise, and zero maintenance remain as requirements that must be met for acceptable performance. Although materials are available that meet some of these requirements, a completely satisfactory solution has yet to be found. The purpose of this investigation is to determine that state of the art of solid lubrication and associated materials systems that may be applicable to electrical contacts in miniature slip rings.

SUMMARY

A survey of the literature and of unpublished investigations of solid lubricants and self-lubricating materials has identified several materials systems that hold promise for development for low-energy, high-reliability contacts in guidance platforms such as the ST-124M. The solid lubricants include both heavy-metal derivatives and solid organic materials. Although only limited studies have been made of self-lubricating materials for miniature slip rings, numerous materials have been developed for brush and commutator service for medium-energy contacts. Appropriate modifications of these materials and of some developed for space-environment bearing applications appear to offer the most hope.

LUBRICATION OF CONTACTS WITH SOLIDS

Solid lubricants for electrical contacts in slip rings can be applied either directly as films on one or both of the rubbing surfaces, or can be incorporated into the contact material itself in the form of a composite. The two approaches are considered separately in a review of the current technologies applicable to electrical contacts.

Solid-Film Lubricants

For the most part, the development of solid lubricants to date have resulted from a need for lubrication of sliding- and rolling-contact systems which are subject to some unusual environments. High and low temperatures, nuclear-radiation environments, and vacuum applications compromise the use of conventional liquid lubricants. Solid lubricants can be effective substitutes in some applications. Solid-film lubricants prevent high friction and wear between mating surfaces by separating the surfaces with a film of low-shear-strength material. Shear occurs within the film, and the resulting friction is largely determined by the shear strength of the lubricant. While thin films of some solid lubricants applied to sliding surfaces by burnishing have the advantages of good stability and reasonably high resistance to degrading environments and require no maintenance, they have the disadvantages of limited life (because of their lack of mobility which leads to replenishment failures), higher friction (higher than that characteristic of hydrodynamic lubrication), and some unavoidable wear of the mating metals (a result of asperity contact through the film). The service life of solid-film lubricants has been increased and the wear of the mating surfaces decreased by using the thicker films which result when the lubricating solid is dispersed in and applied to the surfaces with inert binders. While solid-film lubrication holds some promise as a technique for lubricating – and is directly applicable to – electrical contacts, the requirements of long-life operation with low electrical resistance and low noise make it important to consider the effectiveness of this technique as a function of time.

Graphite was the first widely applied solid-film lubricant. While it is suitable for many sliding systems, its use in extreme environments is limited by its requirement to retain the adsorbed water vapor and gases that are the keys to its lubrication mechanism. Graphite is, therefore, not applicable in vacuum or dry, inert-gas environments.

The failure of graphite to provide adequate lubrication in extreme environments led to the development of solid lubricants from other lamellar structures such as certain sulfides, selenides, and tellurides of metals from Groups IV, V, V-B, VI-B, and VII-B of the Periodic Table. MoS_2, a naturally occurring substance, is an example which finds widespread applicability as a solid lubricant. Several of the other heavy-metal derivatives have been used for applications requiring either higher oxidation stability, radiation resistance, or electrical conductivity. The properties of the heavy-metal-derivative solid lubricants have been tabulated by Magie[1] and are given in Appendix A for reference. Table 1 lists several solid lubricants that may be considered candidates for electrical-contact applications because of their low resistivity and low coefficient of friction. The properties of MoS_2 are included for comparison.

TABLE 1. SOLID LUBRICANTS WHICH EXHIBIT RELATIVELY LOW RESISTIVITY AND FRICTION COEFFICIENT

Lubricant	Resistivity, ohm-cm	Coefficient of Friction
NbS_2	3.10×10^{-3}	0.08
$NbSe_2$	5.35×10^{-4}	0.12
TaS_2	3.33×10^{-3}	0.05
$TaSe_2$	2.23×10^{-3}	0.08
$TiSe_2$	2×10^{-3}	0.17
MoS_2	8.51×10^{2}	0.18

The use of $NbSe_2$ for electrical-contact applications has already been given some study. However, it was chosen essentially on the basis of relatively high conductivity, comparative availability, and low cost. The promise of the other compounds listed in the table as electrical-contact lubricants has not been determined.

In practical studies of solid-film lubricants for electrical contacts, composite films of Ni, Cr, and MoS_2 (or PbS) have been deposited on slip-ring surfaces to thicknesses of about 0.5 μ.[2,3] This multiple-layer concept reportedly promotes improved bonding with the base metal. The results using V-grooved slip rings having brushes loaded to 1.5 grams and peak current of 100 milliamperes showed contact resistances of 0.2 to 0.4 ohms.[3] While this resistance is unacceptable for miniature slip rings, improved resistance might be gained by doping the lubricant with structurally similar high-conductivity materials.[2] Further studies have not been made with this lubricant system, but bearings for rotating anode X-ray tubes and V-grooved slip rings for medium-energy contact applications are currently being coated by the same technique.[4]

Promising results have been reported on the use of MoS_2 burnished on the surface of copper commutators against which precious-metal alloy brushes operate in vacuum environments.[5] With a brush load of 14 grams, a commutator was run in an oscillatory mode for 4 months. Although the circuits were reported to be electrically noisy, the noise levels were low enough to be considered acceptable. Brush and commutator wear was judged to be low. Similarly, coatings of 6-micron-particle-size polytetrafluroethylene (PTFE) on gold-plated crossed rods operating under 250-gram contact loads for 500,000 cycles have effectively controlled wear, contact resistance, and electrical noise to acceptable levels.[6]

In a study of the applicability of solid-film lubricants to potentiometer contacts for satellite applications in vacuum, MoS_2 and $MoSe_2$ have shown consistently low friction and wear for 100,000 rubbing cycles.[7] The results with $NbSe_2$ were inconsistent, but both friction and wear were higher than that for either MoS_2 or $MoSe_2$. No contact resistance or noise measurements were reported.

The results of one continuing study to develop improved high-temperature, solid-film lubricants has some marginal applicability to low-energy electrical contacts in slip-ring applications.[8,9] Bonding techniques are being investigated and include (1) chemical bonding of solid lubricants with pyrophosphate binders, (2) plasma-torch flame spraying of solid lubricants (such as CaF_2, BaF_2, and MoS_2) with metallic binders such as silver, and (3) binding solid lubricants with ceramics. The flame-spraying technique holds the most promise for the application of conductive solid-film lubricants. However, problems in control of the lubricant-binder ratio and oxidation of the solid lubricant in the application process are yet to be solved. Nevertheless, the advantages offered by this technique include the use of gold or silver as the binder phase to form a tightly adhering, conductive, lubricating film that might be used as the electrical-contact surface. The applicability of the above process to electrical contacts has not been investigated. For reference purposes, selected data from this work[9] are presented as Appendix B.

Solid or semisolid organic films have also been investigated as lubricants for electric contacts. In an extensive study for improving the reliability of static connector devices, the solid organic compound octadecylamine hydrochloride (ODA-HCl) has been found to be effective in reducing wear and friction of gold and silver contact surfaces.[10] The low static contact resistance of the substrate metals is not appreciably altered by the presence of the lubricant. To remain effective, films of ODA-HCl require a rather rough surface so that reservoirs of the lubricants are maintained in the contact area.

The application of ODA-HCl to slip rings has not been reported, but it appears to be worthy of some consideration.

Mixtures of paraffin wax and polyphenyl ether liquids have also been reported to be effective boundary lubricants for electrical-contact applications.(11) For a 1/8-inch-hemispherical rider loaded with 100 grams and sliding on a flat at a speed of 1 cm/sec, the contact resistance of gold on gold and silver on silver was less than 0.001 ohms. Measured coefficients of friction were 0.09 and 0.16, respectively. The polyphenyl ether has been previously identified as an effective boundary lubricant for gold.(12) Its combination with paraffin is a mechanical mixture, which results in a paste-like material that is applied to the contact surface.

Certain organic polymers have also been found to be effective thin-film lubricants for electrical contacts.(13) Deposited on the contact surfaces by evaporation from a solvent, a silicone resin was found to be the most effective polymer of the nine types evaluated. This polymer was recommended for use on contacts that could not withstand the application procedures of ODA-HCl.

Self-Lubricating Composite Materials

The incorporation of a solid lubricant in an electrical-contact member to form a composite has a distinct advantage over thin films: that of providing a large reservoir of lubricant which is continuously uncovered as surface wear occurs. Composite materials, therefore, might be less susceptible to the deteriorating effects of lack of film replenishment, which leads to severe wear and high electrical noise.

When graphite composite brushes were found to wear rapidly in high-altitude aircraft motors because of the lack of water vapor, self-lubricating brush materials containing MoS_2 and lithium carbonate were developed as improved brush materials.(14) Other studies showed that composites of silver containing 12 to 15 percent MoS_2, and silver containing 2.5 percent copper and 15 percent MoS_2 were suitable for brushes for power transmission in vacuum.(15, 16, 17) The ring materials included silver, gold, and rhodium. Gold was found to cause the greatest brush wear. In all cases, the current density was from 10 to 140 amps/in.^{2}, values much greater than those found in miniature slip rings. The measured contact resistance was between 1 and 6 milliohms.

Silver brush composites containing 15 percent $NbSe_2$ have also been developed and tested.(18) When compared with identical brushes containing 15 percent MoS_2, the contact resistance of the silver-$NbSe_2$ composite was approximately half that of the silver-MoS_2 composite. The lower contact resistance probably reflects the greater conductivity of $NbSe_2$ compared with that of MoS_2. No information is available concerning the performance of self-lubricating silver composites in low-energy contact applications. A review of some of the data found for rolling and sliding contacts in vacuum is given by Przybyszewski. A portion of this review and the references he cites are reproduced in Appendix C.

An unusual type of self-lubricating material that might have applicability to electric contacts has been developed for high-temperature oxidizing environments.(19) Self-lubricating solids have been prepared that contain 70 to 90 percent WSe_2 and 30 to 10 percent gallium or gallium-indium. The WSe_2 powder is "amalgamated" with the gallium and compacted at high pressures to form a solid. A high-temperature cure results in a hard compact material suitable for high-temperature bearing applications. Although the compacts have not been considered as electrical-contact materials, their resistivity is near that of pure $NbSe_2$ (5×10^{-4} ohm-cm). Doping the compacts with silver as a filler compromises the high-temperature properties, but raises the conductivity. Among existing materials, the silver-doped compacts may, therefore, hold greater promise as self-lubricating contact materials. The compacts cannot be made with the higher conductivity $NbSe_2$ because it is not compatible with gallium. However, the feasibility of using TaS_2 or $TaSe_2$ to increase the conductivity[20] has not been determined, and attempts to make composites containing these solid lubricants appear warranted.

Self-lubricating composite materials, which are produced by hot-press compaction, for use at high temperatures also have potential application to electrical contacts. Compacts containing a minimum of 80 percent solid lubricant, MoS_2 or $NbSe_2$, and varying percentages of boron, tantalum, and molybdenum have been prepared and tested.[8, 9] Some of the compositions containing MoS_2 have already found application as materials for d-c motor brushes for vacuum environments in satellites.[21] The brushes are run against copper commutators at current densities of 40 to 50 amps/in.^{2}. Compared with MoS_2 compacts, the compacts containing $NbSe_2$ have shown very brittle mechanical properties as well as inferior electrical properties. A limited investigation has also been made on the applicability of the MoS_2 compact to slip rings. The best performance was obtained with a 1/8 x 1/4-inch flat brush of the MoS_2 compact material running against a coin-silver ring. Operating conditions of 1.5 volts and 350 milliamperes produced a contact resistance of less than 0.1 ohm. The electrical noise was a function of load and speed; at a sliding speed of 2 ft/min and a load of 11 oz, the electrical noise was approximately 2 millivolts. Improved electrical properties might be expected for the compact doped with silver or gold, but such a compact has not been evaluated.[21] In another study on the use of MoS_2 compacts for electric contacts in potentiometers for satellite (vacuum) applications, the friction and wear characteristics were found to be superior to silver-$NbSe_2$ composites under similar conditions.[7] Friction coefficients of 0.04 to 0.07 were measured in vacuum with negligible wear for 100,000 cycles. Electrical performance was not reported.

Composites of 10 percent $NbSe_2$ and gold have been evaluated for electrical contacts in miniature slip-ring assemblies.[22] The composites were prepared by powder-metallurgy techniques and were sintered at either 500 or 900 C. Friction, wear, and dynamic contact-resistance measurements were made between a Neyoro 28A gold alloy wire rider loaded with 10 grams against the $NbSe_2$-Au composite flat. At sliding velocities of 0.35 mm/sec, the coefficient of friction varied erratically between 0.4 and 2.1 as the number of cycles of reciprocating sliding increased. Dynamic contact resistance was generally about 2 milliohms, but dynamic-resistance spikes from 700 milliohms to open-circuit were observed. Microscopic examination of the composite materials indicated that large agglomerates of $NbSe_2$ were probably responsible for the high-resistance spikes. Wear measurements of the composites after 47,000 cycles showed that the scar depths were 0.001 to 0.002 inch deep. Previously, similar measurements on electroplated gold surfaces lubricated with organic fluids showed scar depths of only 0.00006 to 0.0004 inch. The particular $NbSe_2$-gold composites studied thus exhibited much higher wear, higher friction, and poorer contact properties than did organic-fluid lubricated contacts.

Techniques for preparing and applying $NbSe_2$-gold mixtures to the surfaces of miniature slip rings have been attempted.[23] Composites have been prepared by pressure bonding and by electrodepositing. The electrodeposited composites exhibit less wear in service, which is probably a result of a higher gold hardness.[24] Friction coefficients from 0.3 to 0.4 have been measured for the electrodeposited composites, and electrical noise increases with time of running. Although the electrical noise and wear of the electrodeposited $NbSe_2$-gold composites are greater than that for fluid-lubricated electroplated gold, the respondent suggested that composites permit better reliability in design because their electrical performance tends to remain more constant and predictable than that for fluid-lubricated systems. Further optimization and testing of the composites would be required to make the final judgment concerning their applicability to production slip-ring assemblies.

Finally, Kamoshita, Hirano, and Hara present evidence that PbS incorporated in palladium by powder metallurgy techniques exhibits interesting contact characteristics when the composite is rubbed against pure palladium and gold-plated palladium.[25] Pd-PbS composites were made containing from 0.1 to 9.0 wt % PbS. The contact resistance for Pd-1%PbS versus palladium was approximately the same for Pd-Pd contacts. Higher percentages of PbS gave higher contact resistances. Electrical noise levels were reported highest for palladium rubbing against palladium, less for palladium rubbing against Pd-9%PbS, and least for gold-plated palladium rubbing against Pd-9%PbS. Unfortunately from the standpoint of possible friction and noise considerations, the atmosphere for these measurements contained intentionally added benzene vapor. The addition of PbS to palladium reduces the amount of polymeric contact debris over that formed with Pd-Pd contacts, the object of the authors' experiments.

CONCLUSIONS

The practicability of a solid-film technique for lubricating sliding electrical contacts for miniature slip-ring assemblies depends critically on the durability of the lubricant film, that is, on the expected service life of the assembly. Such films have been shown to be effective lubricants until the wear processes remove them from the surface. A probable requirement, therefore, is a solid-lubricant film which is applied thin enough to permit adequate electrical conductivity at low contact-energy-transfer levels, and yet exhibits sufficient durability to remain effective for the required service life of the device. The possibility of fulfilling these requirements with solid-film lubricants has not been established for miniature slip-ring applications of interest to this program.

As the requirements for slip-ring life are increased, self-lubricating solids that can withstand wear without large changes in electrical performance will be required for electrical-contact members. Composites containing a metallic portion for electrical conduction and a solid-lubricant portion to reduce friction and wear represent the types of materials to which one must turn to fulfill the requirements. Only the $NbSe_2$-gold composite system has been investigated for miniature slip-ring applications. Other composite materials developed for brush-commutators and for bearing applications indicate some promise, but have yet to be evaluated for slip-ring applications. The possible utility of many of the solid lubricants having conductivities comparable with that of $NbSe_2$ is yet to be determined. Combinations of conductive solid lubricants with many possible metal matrices to make composites are available for future evaluation as practical self-lubricating electrical-contact materials for miniature slip rings.

REFERENCES

(1) Magie, P. M., "A Review of the Properties and Potentials of the New Heavy Metal Derivative Solid Lubricants", Lubrication Engineering, 262-269 (July, 1966).

(2) Taylor, R. C., "Lubrication Research and Development Programs at CBS Laboratories", Space Lubrication Conference, Proceedings (September, 1963), pp 197-199.

(3) Jamison, W. E., "Lubricant Coating for Vacuum Slip Rings", Engineering Seminar on Electric Contact Phenomena, Proceedings (June, 1963).

(4) Azud, R., CBS Laboratories, personal communication, (June, 1968).

(5) Vest, C. E., and Bowden, W. W., Jr., "Evaluation of Space Lubricants Under Oscillatory and Slow Speed Rotary Motion", ASLE Preprint No. 67AM8A-5, (May, 1967).

(6) Solos, L. P., "Fundamental Study of a Gold Plating and Dry Film Lubricant System for Long Life Sliding Electric Contacts", National Aerospace and Electronics Conference, Proc. Dayton, Ohio (May, 1964), pp 117-123.

(7) Jones, J. R., "Friction and Wear of Potentiometer Contacts in Vacuum", Wear, 11 (5), 355-367 (1968).

(8) Hopkins, V., et al, "Development of New and Improved High-Temperature Solid Film Lubricants", Technical Report ML-TDR-64-37, Part III, (August, 1966).

(9) Hopkins, V., et al, "Improved High-Temperature Solid Film Lubricants", Technical Report AFML-TR-67-223, Part I, (July, 1967).

(10) Steinberg, G., "High Reliability Connective Devices", Final Report, AD 653847 (June, 1967).

(11) Chiarenzelli, R. V., and Henry, B. C., "Lubricating Separable Electric Contacts and Tarnish Prevention", Lubrication Engineering, 174-180 (May, 1966).

(12) Antler, M., "The Lubrication of Gold", Wear, 6, 44-65 (1963).

(13) Steinberg, G., Saunders, J. B. and Planting, P. J., "High Reliability Connective Devices", Semi-Annual Technical Report No. 1 (August, 1964).

(14) Nelson, R. E., "Improved Carbon Brushes for Aircraft Electrical Machines", Stackpole Carbon Co., WADC TR-57-170 (January, 1960).

(15) Clauss, F. J., and Kingery, M. K., "Sliding Electrical Contact Materials for Use In Ultrahigh Vacuum", Proc. of the Sixth Structures and Materials Conference, AIAA, Apr. 5-7, 1967, pp 172-184.

(16) Murray, S. F., and Marx, H. E., "Evaluation of Slip Rings for Spatial Applications", General Electric Report 61GL85 (March, 1961).

(17) Salmon, W. A., and Scammell, H., editors, "Lubrication in Space", Baird-Atomic, Inc., and Arthur D. Little, Inc. (1963).

(18) Moberly, L. E., and Johnson, J. L., "Electrical Sliding Contacts for Application in Space Environments", Supp. to IEEE Trans. on Aerospace (June, 1965), pp 252-257.

(19) Boes, D. J., "Unique Solid Lubricating Materials for High Temperature Air Applications", ASLE Paper No. 66LC-3, Lubrication Conference (October, 1966).

(20) Boes, D. J., Westinghouse Research Laboratories, personal communication (June, 1968).

(21) Van Wyk, J. W., The Boeing Company, personal communication (June, 1968).

(22) Battelle Memorial Institute Reports to Poly-Scientific Division, Litton Precision Products, Inc., February 14, 1967, and January 23, 1967.

(23) Poly-Scientific Division of Litton Precision Products, NASA Contract No. NAS 8-20578.

(24) Glossbrenner, E. V., Poly-Scientific Division, personal communication (June, 1968).

(25) Kamoshita, G., Hirano, M., and Hara, N., "Inhibiting Effect of PbS Addition to Brown Powder Formation on Palladium Alloys", Third International Research Symposium on Electrical Contact Phenomena, University of Maine (June, 1966).

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APPENDIX A

SOME PROPERTIES OF HEAVY-METAL-DERIVATIVE SOLID LUBRICANTS, FROM MAGIE (REFERENCE 1)

TABLE A-1. SOME PROPERTIES OF HEAVY-METAL-DERIVATIVE SOLID LUBRICANTS, FROM MAGIE (REFERENCE 1)

Compound	Crystal Structure	Color	Molecular Weight	Actual Density, g/cm	Lattice Parameter (A-Dir.), A	Lattice Parameter (C-Dir.), A	Vacuum Stability, C	Air Stability, C	Resistivity, ohm-cm	Conduction Type	Comparative Coefficient of Friction
Graphite	Hexagonal	Gray-black	12.01	2.25	2.455	6.69	Not stable	350	2.64×10^{-3}	Metal	0.20
Cr_2S_3	Trigonal	Brown-black	200.18	3.972	5.941	11.18	1350	--	(a)	(a)	--
Cr_2Se_3	Rhombohedral	Gray	340.9	--	--	--	--	--	(a)	(a)	--
Cr_2Te_3	Hexagonal	Gray	486.8	--	3.981	6.211	--	--	(a)	(a)	--
MoS_2	Hexagonal	Gray	160.07	4.80	3.16	12.295	1350	350	8.51×10^{2}	P-semi	0.18
$MoSe_2$	Hexagonal	Gray	253.86	6.9	3.29	12.80	1350	400	1.86×10^{-2}	Metal	0.17
$MoTe_2$	Hexagonal	Gray	351.14	7.7	3.52	13.97	1240	400	8.69×10^{2}	P-semi	0.19
WS_2	Hexagonal	Gray	247.98	7.50	3.29	12.97	1350	440	1.44×10^{1}	N-semi	0.17
WSe_2	Hexagonal	Gray	341.78	9.0	3.29	12.95	1350	350	1.14×10^{2}	P-semi	0.09
WTe_2	Orthorhombic	Gray	439.05	9.4	--	--	1020	--	3.10×10^{-3}	Metal	0.49
VS_2	Hexagonal	Gray	115.06	--	3.29	5.66	450	--	(a)	(a)	--
VSe_2	Hexagonal	Gray	208.86	--	3.34	6.12	450	500	(a)	(a)	0.22
$VTe\delta$	Hexagonal	Gray	178.54	6.80	3.942	6.126	1000	--	(a)	(a)	--
NbS_2	Hexagonal	Gray	157.03	4.41	3.31	11.89	1050	420	3.10×10^{-3}	Metal	0.08
$NbSe_2\beta$	Hexagonal	Gray	250.43	6.25	3.449	13.03	1350	350	5.35×10^{-4}	Metal	0.12
$NbTe_2$	Trigonal	Gray	348.11	7.6	10.904	19.39	--	325	5.74×10^{-4}	Metal	0.53
$TaS_2\beta$	Hexagonal	Gray-black	245.08	7.05	3.346	12.32	900	600	3.33×10^{-3}	Metal	0.05
$TaSe_2\alpha$	Hexagonal	Gray	338.87	8.6	3.431	12.737	900	575	2.23×10^{-3}	Metal	0.08
$TaTe_2$	Trigonal	Gray	436.15	9.4	10.904	20.075	--	320	1.37×10^{-3}	Metal	0.53
TiS_2	Hexagonal	Bronze	112.0	3.28	3.408	5.702	950	130	8×10^{-3}	N-semi	0.22
$TiSe_2$	Hexagonal	Dark purple	205.8	5.26	3.535	6.004	950	300	2×10^{-3}	Metal	0.17
$TiTe_2$	Hexagonal	Black	303.1	6.34	3.760	6.480	950	300	1×10^{-4}	Metal	0.33
ZrS_2	Hexagonal	Violet brown	155.4	3.82	3.662	5.809	950	100	1×10^{1}	N-semi	0.22
$ZrSe_2$	Hexagonal	Purple brown	249.1	5.48	3.770	6.137	950	130	1×10^{-1}	N-semi	0.18
$ZrTe_2$	Hexagonal	Purple brown	346.4	6.36	3.952	6.660	950	250	1×10^{-3}	Metal	0.23
HfS_2	Hexagonal	Purple brown	242.6	6.03	3.635	5.837	940	--	1×10^{6}	Non-cond.	--
$HfSe_2$	Hexagonal	Dark brown	336.4	7.46	3.748	6.159	940	--	2×10^{1}	N-semi	--
HfTe	--	--	--	--	--	--	--	--	--	--	--
ReS_2	Hexagonal	Black	250.33	--	3.14	12.20	1000	225	--	--	--
Re_2Se_7	Hexagonal	Black	925.10	--	--	--	750	850(b)	--	--	--
Re-Te	--	--	--	--	--	--	--	--	--	--	--
ThS_2	Orthorhombic	Purple brown	296.2	7.36	--	--	1900	1900(b)	1.0×10^{7}	Non-cond.	--
$ThSe_2$	Orthorhombic	Dark gray	389.9	--	--	--	1000	--	1.5×10^{5}	P-semi	--
$ThTe_2$	Hexagonal	Black	487.2	--	8.49	9.01	950	1900(b)	2×10^{-2}	Metal	--
$US_2\delta$	Hexagonal	Black	302.16	8.175	7.238	4.059	1200	1900(b)	Non-conductor		--
USe_2	Orthorhombic	Black	395.95	9.0	--	--	1400	--	3.34×10^{-2}	Metal	--
$UTe\beta$	Hexagonal	Black	493.23	8.9	3.998	7.156	1200	--	1.20×10^{-2}	Metal	--

(a) Chromium and vanadium derivatives vary in resistivity under heat and magnetic force. (b) Unconfirmed results.

APPENDIX B

SELECTED DATA FROM HOPKINS, ET AL. (REFERENCE 9) CONCERNING CERTAIN SOLID LUBRICANT COMPACT COMPOSITIONS

TABLE B-1. SELECTED DATA FROM HOPKINS, ET AL. (REFERENCE 9) CONCERNING CERTAIN SOLID LUBRICANT COMPACT COMPOSITIONS

Composition, percent					Fabrication Temperature, F	Ultimate Flexural Stress, psi	Ultimate Compressive Stress, psi	Electrical Resistance, ohms[a]	Wear Rate, Inches/Hour, at 3000 ft/min and 100 Psi Load
MoS_2	$NbSe_2$	B	Ta	Mo					
80	--	20	--	--	2600	8,900	26,000	0.042	0.060
--	80	20	--	--	2800	5,920	(b)	0.084	(b)
--	80	--	20	--	2800	9,510	33,100	0.061	0.0190
80	--	10	10	--	2800	13,200	16,400	0.057	(b)
90	--	5	5	--	2800	6,050	10,600	0.082	0.0030
85	--	5	5	5	2800	13,900	16,900	0.095	0.0044
91	--	3	3	3	2800	13,900	8,430	0.165	(c)
85	--	5	3	7	2800	10,600	8,970	0.125	(c)
85	--	7	3	5	2800	9,500	9,550	0.080	(c)
85	--	5	5	5	2700	7,360	8,700	0.097	(c)
85	--	5	3	7	2700	7,160	7,400	0.100	(c)
91	--	3	3	3	2700	6,570	11,400	0.180	(c)
85	--	7	3	5	2700	7,180	13,300	0.105	(c)
85	--	5	5	5	3000	9,930	(c)	0.030	(c)

(a) Resistance values have meaning only relative to one another.
(b) Specimen damaged during machining.
(c) No test conducted.

APPENDIX C

SUMMARY OF DATA ON SLIDING AND ROLLING CONTACTS IN VACUUM, FROM PRZYBYSZEWSKI (REFERENCE C-1)

TABLE C-1. SUMMARY OF MATERIALS EMPLOYED IN VARIOUS SLIDING ELECTRICAL CONTACT EXPERIMENTS IN VACUUM, FROM PRZYBYSZEWSKI, (REFERENCE C-1)

Brush Material	Lubricant	Brush Material Composition	Ring Material	Remarks	Reference
Silver-MoS_2	MoS_2	88% silver, 12% MoS_2	Silver Rhodium plated silver	Acceptable for use in vacuum. Better performance in vacuum than in air.	C-2
Silver-copper-MoS_2	MoS_2	82.5% silver, 15% MoS_2 2.5% copper	Electroplated silver Electroplated gold	Addition of copper hardens silver, resulting in less brush wear. Gold rings caused greater brush wear.	C-3
Silver-molybdenum-MoS_2	MoS_2	--	--	Poor results, erratic performance, excessive noise, brush arcing.	C-3
Silver-$NbSe_2$	$NbSe_2$	85% silver, 15% $NbSe_2$ (not optimized)	Coin silver (90% silver, 10% copper)	Slightly greater wear than equivalent MoS_2 compacts. Better noise performance in vacuum.	C-4
Silver-graphite	Graphite	80% silver, 20% graphite	Pure silver Electroplated silver	Extremely poor performance in vacuum. Slightly better than equivalent MoS_2 compacts for atmospheric use.	C-2, C-3, C-5
Precious metal alloy wire	Synthetic ester Chlorinated silicone Hydrocarbon diffusion pump oil	Proprietary	V-grooves of hard gold plate on silver	Lubrication in vacuum supplied by evaporation of fluid in semisealed container. Synthetic ester gave best performance. Hydrocarbon oil gave poorest performance. Slip rings ran with low noise for 79 days.	C-2

TABLE C-2. SUMMARY OF MATERIALS EMPLOYED IN VARIOUS ROLLING ELEMENT ELECTRICAL CONTACTS IN VACUUM, FROM PRZYBSZEWSKI (REFERENCE C-1)

Ball Material	Race Material	Retainer Composition	Lubricant	Remarks	Reference
440-C stainless steel: gold plated	Both races 440-C stainless steel: gold plated	85% gold, 15% MoS_2	MoS_2	Bearing given light, initial application of MoS_2 before running. Best running of several combinations of materials used.	C-6
440-C stainless steel: gold plated	Both races 440-C stainless steel: gold plated	Teflon, glass fiber, MoS_2 composition	Teflon, MoS_2	Operated well mechanically, but electrically noisy in both air and vacuum.	C-6
Tungsten-cobalt-chromium tool steel	Tungsten-cobalt-chromium tool steel	No retainer Full complement of balls	Silver film applied to balls only	Good operation in vacuum (10^{-8} torr or 1.33×10^{-6} N/m^2) temperatures to 600° C and speeds to 10,000 rpm. Used for rotating anode X-ray tube bearings.	C-7, C-8
Tungsten-cobalt-chromium tool steel	Tungsten-cobalt-chromium tool steel	Not known	Evaporated barium film	Good lubrication and wear if cobalt, chromium, or aluminum are deposited as an intermediate layer. Early work on rotating anode X-ray tube bearings.	C-9
52100 Steel	52100 Steel	Laminated phenolic	Chlorinated methyl-phenyl silicone (vacuum impregnated)	Microscopic pitting damage observed at currents as low as 0.167 ampere. Voltage drop across bearing gradually decreased during test.	C-10

REFERENCES FOR APPENDIX C

(C-1) Przybyszewski, J., "Lubrication of Sliding and Rolling Element Electrical Contacts in Vacuum", ASLE Preprint No. 68AM 4C-3 (May, 1968).

(C-2) Salmon, W. A., and Scammell, H., editors, "Lubrication in Space", Baird-Atomic, Inc., and Arthur D. Little, Inc. (1963).

(C-3) Clauss, F. J., and Kingery, M. K., "Sliding Electrical Contact Materials for Use in Ultrahigh Vacuum", Proceedings of the Sixth Structures and Materials Conference, AIAA, Apr. 5-7, 1967, pp. 172-184.

(C-4) Moberly, L. E., and Johnson, J. L., "Electrical Sliding Contacts for Application in Space Environments", IEEE Trans. on Aerospace, AS-3, Supp. (June, 1965), pp. 252-257.

(C-5) Blackmon, P. H., Clauss, F. J., Ledger, G. E., and Mauri, R. E., "Materials Evaluation Under High Vacuum and Other Satellite Environmental Conditions", Rep. no. 3-77-61-23, Lockheed Aircraft Corp. (January, 1962).

(C-6) Devine, E. J., "Rolling Element Slip Rings for Vacuum Application", NASA TN D-2261 (1964).

(C-7) Kessler, G. R., and Mahn, G. R., "Factors Affecting Design and Operation of Rolling Element Bearings in Rotating Anode X-ray Tubes", Lubrication Eng., 23 (9), 372-379 (September, 1967).

(C-8) Goetzel, B. G., and Singletary, J. B., editors, Space Materials Handbook, Addison-Wesley Publ. Co. (1965).

(C-9) Atlee, Z. J., Wilson, J. T., and Filmer, J. C., "Lubrication in Vacuum by Vaporized Thin Metallic Filma", J. Appl. Phys., 11 (9), 611-615 (September, 1940).

(C-10) Murray, S. F., and Lewis, P., "Effect of Electrical Currents on Ball Bearings Damage in Vacuum and in Air", Lubrication Eng., 23 (9), 363-371 (September, 1967).

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